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■ RESEARCH ARTICLE

The Extreme Cold in the Context of a Warmer Planet and a Cooler Solar Cycle

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ABSTRACT: While climate change leads to higher global mean temperatures, more frequent extremely cold events (ECE) have been reported in many places in the past few years. Recent studies on extreme weather are primarily focused on extreme heat, floods, and wildfires. Extreme cold is much less studied. However, extreme cold could cause severe economic damage, human threats, and global transportation disruption.

In addition, our solar system is experiencing a weak solar cycle (SC), which raises interesting questions about the Sun-climate interaction. While SC impacts on the climate are mainly in the stratosphere and above, there could be indirect effects at the surface. How ECEs change in the context of a warmer planet and a cooler SC is a fascinating but rarely studied topic.

We analyzed the ECE frequency and its possible correlation with the SC using temperature data from NOAA at five selected stations during the past five decades. The results do not suggest a decreasing trend in ECEs. Some stations even show increasing trends of ECEs. At one station, we found a possible correlation between ECEs occurrences with the SC, which could be the first evidence of SC impacts on the surface ECEs.

KEYWORDS: Earth and Environmental Sciences; Climate Science; Atmospheric Science; Extreme Cold Events; Solar Cycle.

■ Introduction

While anthropogenic climate change has caused higher global mean temperatures, prolonged heat waves, and more frequent wildfires and floods, many places worldwide still experience intense winter storms and polar vortex warnings almost every winter. For example, the extreme cold event in January 2019 due to a polar vortex breakdown caused extreme temperatures as low as -50 °C in Minnesota.[1] In the meantime, our solar system just went through a surprisingly weak solar 11-year cycle (Solar Cycle 24) and approaching the peak of Solar Cycle 25, which is expected to be another weak one.[2] Given that the Maunder Minimum, a period of several decades with very weak solar cycles, coincided with the Little Ice Age, a long period of lower-than-average temperatures, there have been concerns about the possible impacts of consecutive weak solar cycles on our planet's temperature. However, others argue that the direct effect on the surface temperature should be minimal since the solar forcing mainly affects the stratosphere and above. There is no solid evidence about the solar cycle's impact on extreme cold events.

Accordingly, a question might be: will we have fewer extreme cold events in the context of a warming planet and a cooler solar cycle?

Based on the literature, extreme cold events (ECE), which are defined as temperature anomalies significantly lower than the normal range at the time of year in the specific location, have been reported more frequently in various terrains, countries, and latitudes in past years,[3-5] though global warming and more frequent extreme heat events are of greater interest to climate scientists and the general public.

According to the World Meteorological Organization (WMO), the global number of weather-related disasters has increased five-fold over the past 50 years. Many studies have been done on extreme weather, but most of the research has focused on extreme heat, storms, floods, wildfires, and tornadoes.[6] In contrast, extreme cold is much less studied, which is not surprising given the big picture of our warming planet.

However, extreme cold could cause severe damage, threat, and interruption to everyday life. People exposed to extreme cold could suffer threats to health and safety both physically and psychologically (cold stress, injury, and death).[7-10] Temperature during extremely cold weather was significantly associated with increased mortality. For example, a decrease of 1 degree in mean temperature significantly increased mortality by 2.8% in a recent study on mortality in Greece during extreme cold events.[8] A recent study focused on the influence of extreme cold events on mortality in the United States suggests that early-season ECEs result in a much higher relative risk of increased mortality, particularly in cities with higher mean winter temperatures, since individuals tend to be more vulnerable when not acclimatized to extreme cold.[9] More surprisingly, recent extreme cold events can extend all the way to Texas and even Florida, leading to unexpected emergencies and possible disasters (See Figure 1).[11] The economic effects and the disruption to regional and global transportation due to extreme cold events and the snow storms accompanying them have become significant concerns.[3]

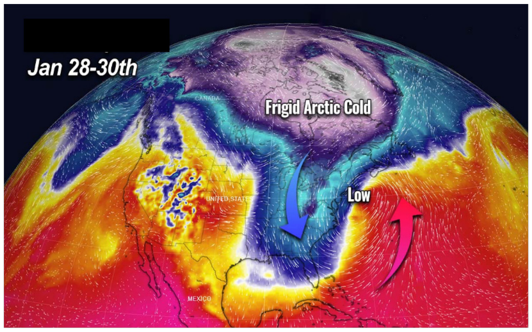

Figure 1: The most recent large-scale extreme cold event with impacts on half of the US.[11]

The causes of the extreme cold events and the mechanisms controlling them are very complex, including but are not limited to large-scale meteorological patterns (LMPs), the Northern Annular Mode (NAM), the Arctic Sea ice extent, La Niña events, sea surface temperature, the polar vortex, gravity waves, and anomalies in global circulations.[4,5] Even with today's high-resolution global 3D climate models and complex assimilation of the circulations, scientists still cannot fully understand the mechanisms or accurately predict the occurrence of such events.[12]

The currently available literature is limited and mainly focuses on specific events or extreme cold waves (ECW) of specific years. Little attention has been paid to the general trend of the frequency of extreme cold, its possible correlations to the various natural and anthropogenic forcings, and the evaluation of its role in the context of massive global warming and the changing solar forcing in the past few decades.

Considering the impacts of extreme cold and the limited research on this topic, we decided to investigate the long-term change in the frequency of extreme cold events. Our goal is to find the patterns of the occurrence of these events after removing the baseline due to global warming and to discover its possible link to the solar cycle. We started with Minnesota and then extended our study to other locations with various latitudes and local climates.

■ Data

Temperature Data:

NOAA (National Oceanic and Atmospheric Administration) National Centers for Environmental Information provides historical temperature data from stations all over the country. All data are publicly available through https://www.ncdc.noaa.gov/cdo-web/datasets. The daily minimum temperature is used to investigate the trend of the occurrences of extreme cold. To accurately separate the long-term baseline (due to global warming) and extract the daily temperature deviation from its normal range, we choose stations with at least 50 years of continuous measurements.

To investigate the potential differences in patterns of extreme cold events between different types of locations (e.g., major cities vs. rural areas, humid climate vs. dry climate, inland areas vs. coastal areas, cold winter vs. mild winter), we carefully chose the following stations to cover various types of comparisons for our study.

Table 1: Summary of the selected locations for this study.

Station	Latitude	Longitude	Inland/Coast	Humidity	Winter
Minneapolis, MN (MSP Airport)	44.88 °N	93.22 °W	Midwest Inland	Humid	Very cold
New York, NY (JFK International Airport)	40.64 °N	73.76 °W	East Coastal	Humid	Cold
Houston, TX (Houston William P. Hobby Airport)	29.65 °N	95.28 °W	South Coastal	Humid	Warm
Las Vegas, NV (Las Vegas Municipal Airport)	35.66 °N	105.14 °W	West Inland	Dry	Cold
Death Valley, CA (Death Valley National Park)	35.46 °N	116.87 °W	West Inland	Dry	Warm

All the chosen weather stations are reliable long-term stations with continuous daily measurement data from 1970 or earlier to the present day. The main characteristics of each location's climate are described here, which shows the reason for them to be selected for this study:

- Minneapolis, MN: Because of its location in the center of North America, Minneapolis is subjected to some of the broadest temperature ranges in the United States. With no natural barriers to block cold air from pouring south from Canada, the arctic air masses often significantly impact the temperature in Minnesota. The polar vortex occurrences have been more frequent during the past years, bringing extremely low temperatures and strong winds in many winters, making the Twin Cities known as the coldest major city in the country.
- New York, NY: As the largest mega city in the United States, New York plays an important role in the country's economy. JFK International Airport is also one of the world's largest and busiest air hubs. The extreme cold events and the accompanying snow storms have been a considerable problem causing countless flight cancelations/delays, large-scale blackouts, and life-threatening living conditions, especially for low-income residents and the homeless, almost every winter.
- Houston, TX: As the largest city in the southern United States, Houston usually has very hot summers and mild winters. It opens to the Gulf of Mexico through Galveston, making it vulnerable to the increasing danger of hurricanes due to climate change. At the same time, the more frequent and stronger polar vortex impacts can extend from Canada through Texas, causing extreme cold events that the local infrastructure and residents are unprepared for.
- Las Vegas, NV: Based on previous reports, the polar vortex breakdown often has the largest impact on the east part of the country due to its moving direction. Moreover, the mountains in the west often help block the southward cold air. This region is thus expected to be less impacted by these events. Therefore, the trend of the occurrences of extreme cold cases in Las Vegas might be very different from the regions affected by the polar vortex.
- Death Valley, CA: Death Valley holds the world record for the highest temperature of 134 ^{o}F (56.7^{o}C) in July 1913

and the highest 24-hour average temperature of 118.1 ºF (47.8 ºC) in July 2021.[13] It is known for extremely dry and hot summer days. With global warming and more frequent heat waves worldwide, it is quite surprising that Death Valley has not broken its own highest temperature record set over a century ago. Although its winter is warm, there are still sub-zero temperatures. The pattern and trend of the coldest events and how they compare with those from much colder locations can be an interesting topic that is not reported in the literature.

Solar Irradiance Data:

The Laboratory for Atmospheric and Space Physics (LASP) center (http://lasp.colorado.edu/lisird/) provides the long-term composite of solar ultraviolet (UV) irradiance data in various wavelengths and time resolutions. The data came from multi-generations of satellite instruments. Solar Lyman-α (at 121.5nm) has been widely used as an index for solar UV irradiance. The long-term composite of annual mean Lyman-α is thus selected to be used in this study as an indicator of the solar cycle.

Methods

To accurately quantify the frequency of extreme cold, the criterion for such events must be carefully defined. We need to consider (1) the local climate, (2) the temperature baseline over the 50-year period, and (3) the average seasonal variation. The winter readiness of the infrastructure and the residents is different for different locations with different latitudes and local climates. Therefore, the standard for coldness depends on these localized conditions. For example, -55ºF (-45.5ºC) is considered an extremely cold temperature for a cold climate like Minnesota, but 20ºF (-6.6ºC) would be a very mild winter temperature for Minnesotans. However, such a "mild" temperature is rare and definitely an extreme cold event and could lead to a large-scale disaster in a warmer climate in Texas or Florida.

Moreover, global warming has caused a quite significant increase in the temperature baseline. Today's "normal" temperature would be warmer than half a century ago. Suppose absolute temperature thresholds are used as the cutoff in the data analysis. In that case, some disaster events in recent years might not be considered that extreme in the last century.

In addition, every climate has its own characteristic seasonal variation, largely dependent on latitude. A fall or spring temperature that is surprisingly lower than the historical average on that day could cause colossal disruption even though it is not much colder than its winter average. As mentioned earlier, early-season ECEs result in a much higher relative risk of increased mortality, particularly in cities with higher mean winter temperatures.[9]

Absolute Cutoff Method: Not Considering the Baseline or the Seasonal Variation:

If an arbitrarily determined absolute threshold for each station is used to count the ECEs, the resulting number of "extreme cold" cases in each winter (November – March) is summarized in Figure 2.

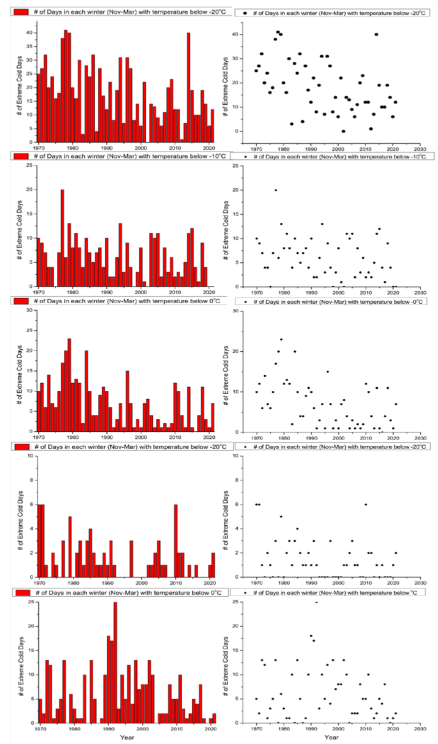

Figure 2: Absolute cutoff method - Summary of the number of ECEs and their trend during 1970 – 2022 in each selected station.

In all stations, the frequency of the "extreme cold" cases shows a decreasing trend over the past 50 years. This apparent result is mainly due to global warming and the increase of the baseline temperature, which is not factored in this method of using an "absolute" cutoff.

Instead, the extreme cold should be characterized by the anomaly with respect to the historical average temperature range on a specific day in a particular region.

Anomaly Method: The Variation from the "Normal" Range (the Increasing Baseline plus the Seasonal Climatology):

Using the data at the MSP airport station as an example, the step-by-step analysis method, which considers the increasing baseline due to global warming and the historical seasonal climatology, is shown in Figures 3 – 5 and described in the following:

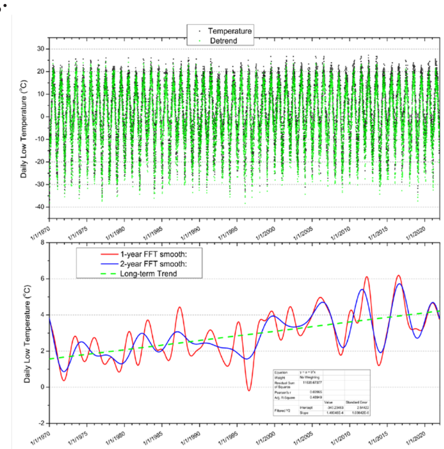

Figure 3: Upper: The time series of the daily low temperature before and after removing the baseline trend in the MSP station at Minneapolis, MN, from 1970 to 2022. Lower: The FFT smoothing results of the time series and the corresponding linear fit (the baseline trend).

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Figure 3 used an FFT (Fast Fourier Transform) filter to smooth out the seasonal variations. The 1-year FFT result (the red line) still shows significant waves likely due to QBO (Quasi-Biennial Oscillation) and other atmospheric dynamics. The 2-year FFT (the blue line) smooths out the QBO signal and the annual seasonal cycle. Then it is much easier to apply a simple linear fit to determine the long-term baseline due to global warming. The linear fit generates a correlation coefficient R of 0.7 and a slope equivalent to an increased rate of 0.5 °C/decade. If the linear fit is directly applied to the raw temperature data, the correlation would be much worse due to the large seasonal oscillation, and the resulting slope would be less accurate.

After removing the baseline trend from the raw data, the "detrended" temperature is shown in the upper panel of Figure 3 as the green scatters. The next step is to quantify the average seasonal variation.

In Figure 4, the detrended data points are plotted against the day of the year (DOY). Because the long-term increasing trend has been removed, the scatters of these data points clearly define a seasonal variation. For each day in Figure 4, there are over 50 data points (one point per year). The average of these points is considered the seasonal climatology temperature of the corresponding day of the year (red dot).

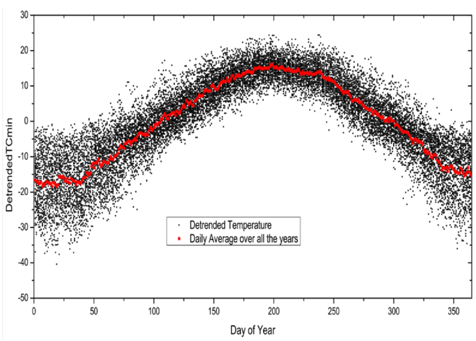


Figure 4: The detrended temperature (black) plotted against the Day of Year (DOY) for all data points in 1970 – 2022 and the average value over all the years for each day (red).

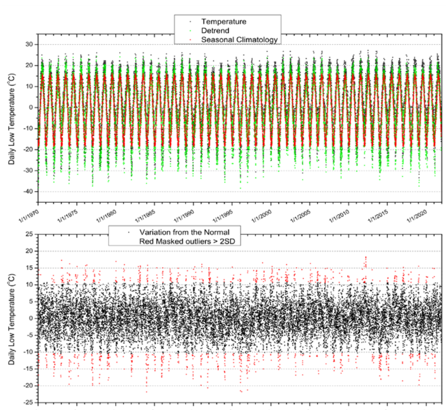


Figure 5: Upper: Time series of daily low temperature (black), detrended temperature (green), and seasonal climatology (red). Lower: The anomaly of the daily low temperature is determined by the variation from the "normal" value. The outliers (> two times the standard deviation) are marked red.

With the seasonal climatology shown in Figure 4, a long-term seasonal cycle is built for all the years during 1970 – 2022, as shown in Figure 5 (red scatters in the upper panel). The sum of the long-term baseline trend and the seasonal cycle is used as the "normal" daily low temperature. The variation from this "normal" value is thus considered an anomaly for each day of the year (lower panel in Figure 5). Most anomaly data points are within the range of two times the standard deviation (SD). The outliers that fall out of the 2SD range are considered extreme cases (red scatters in the lower panel of Figure 5). For this study, the high anomaly values are ignored. The low anomaly values are taken as the extreme cold cases.

Similarly, the data from all other stations in Table 1 are also analyzed with the same approach. The step-by-step results are shown in Figures 6-9.

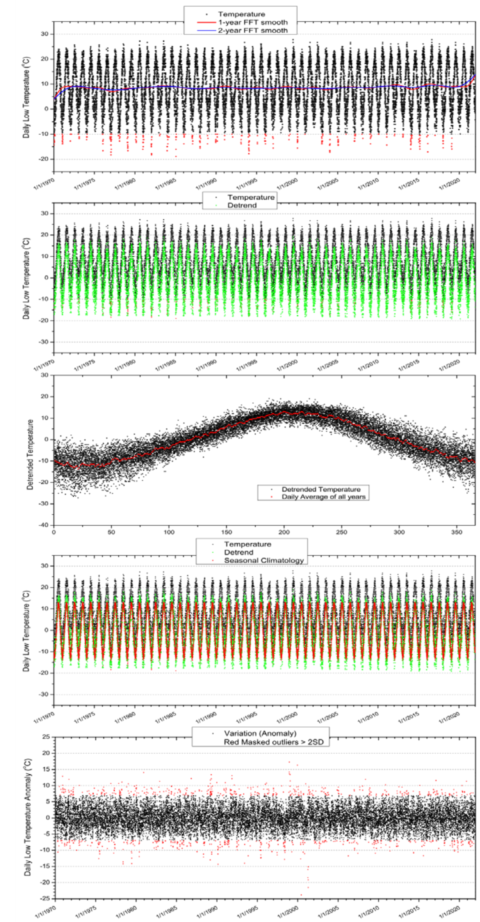
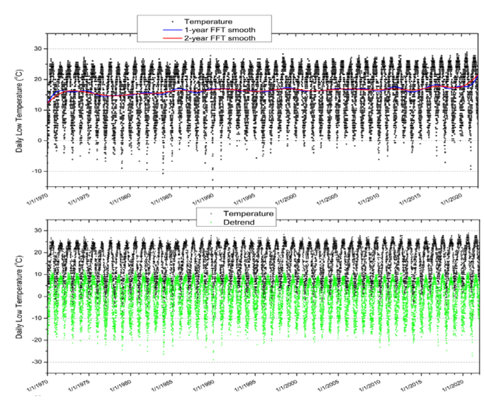


Figure 6: Summary analysis results for the New York station (explanations of the steps are the same for the Minneapolis station in Figures 3-5.



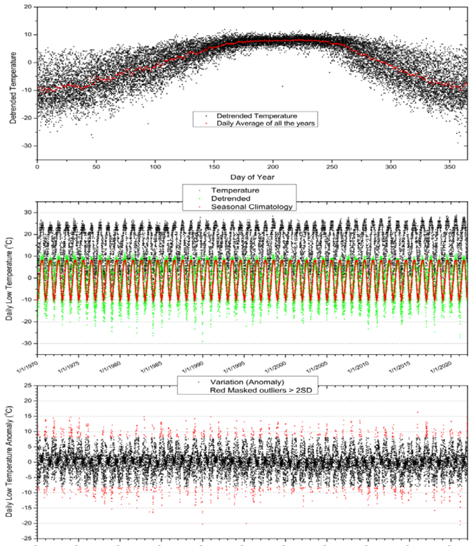


Figure 7: Summary analysis results for the Houston station (explanations of the steps are the same for the Minneapolis station in Figures 3-5.

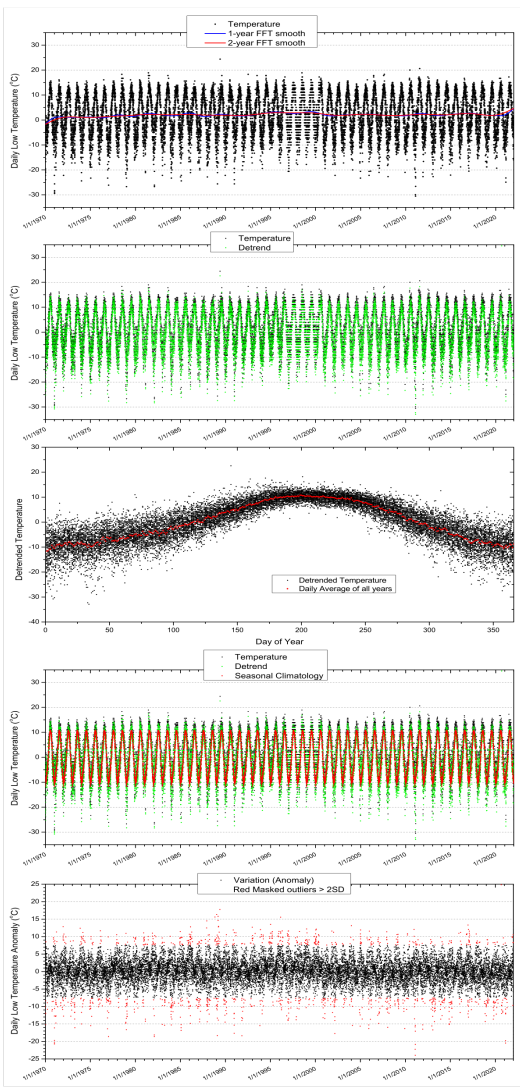


Figure 8: Summary analysis results for the Las Vegas station (explanations of the steps are the same for the Minneapolis station in Figures 3-5.

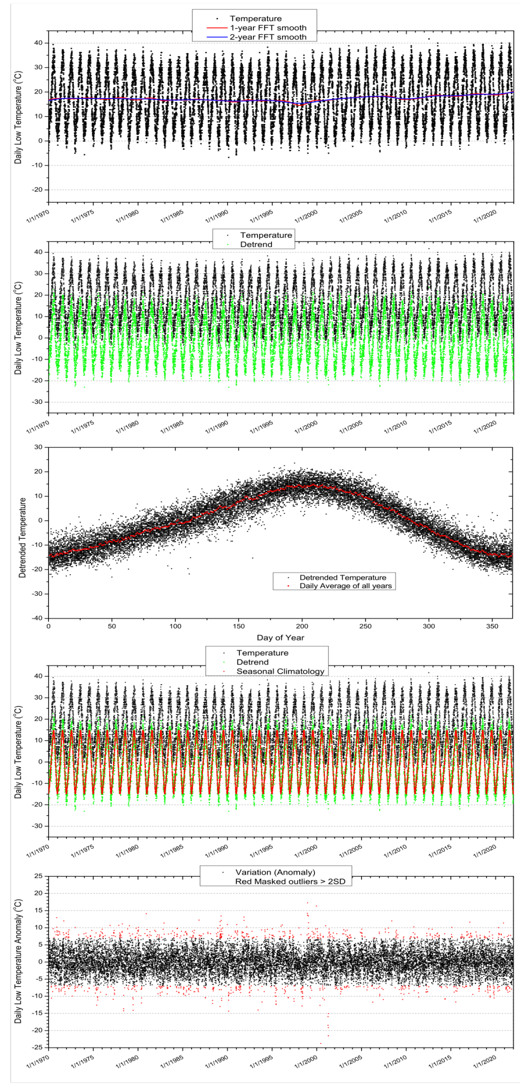
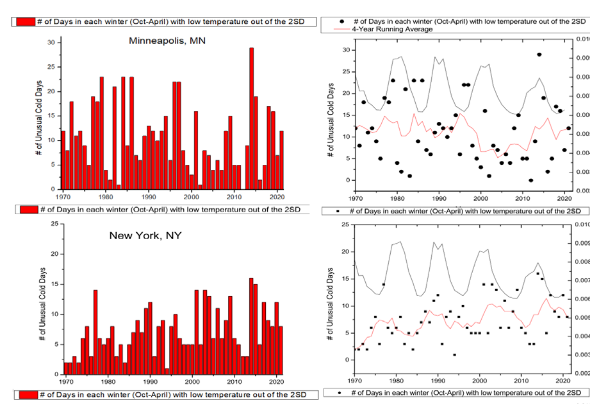


Figure 9: Summary analysis results for the Death Valley station (explanations of the steps are the same for the Minneapolis station in Figures 3-5.

For each station, the number of extreme cold cases is counted for each winter (October – April) and summarized in Figure 10. Note that in the "absolute" threshold method, the extreme cold cases are all in November – March. Still, in the "anomaly" method, the unusually cold cases often extend into fall and spring. Therefore, a wider winter window (October – April) is used in this method.



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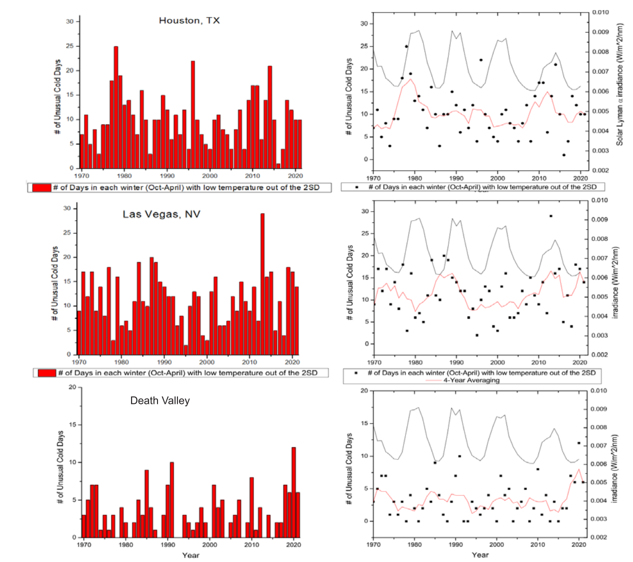

Figure 10: Summary of Anomaly method results - The annual count of ECEs and their trend from 1970 to 2022 in each station. The red line is the 4-year average of the annual count. The black line is the solar UV irradiance.

Results and Discussion

In contrast to the “absolute” threshold method in Figure 2, the “anomaly” method results in Figure 10 do not show a significant decreasing trend in the frequency of the ECEs. More interestingly, in some cases (e.g., New York), a clear increasing trend is suggested, which is more consistent with the growing concerns of extreme cold and the corresponding impacts in many places.

The polar vortex is formed in the stratosphere during polar winter, holding air with very low temperatures above the polar region. In most cases, it is relatively stable throughout the winter. However, sudden stratospheric warming (SSW) events can occur and dramatically weaken the polar vortex or even reverse its direction, leading to the breakdown of the polar vortex and the spread of extreme cold air.[14]

Although the causes of extreme cold are complex and varied, these polar vortex breakdowns are one of the leading causes of large-scale and persistent extreme cold. For example, the four-day-long cold disaster with harsh temperatures as low as -55°F (-48°C) in Minnesota in January 2019[1] and the unprecedented Valentine’s Day cold disaster in Texas in 2021[15] were both due to the breakdown of the polar vortex.

Many scientists have investigated the cause of the SSW events. Currently, it is still not completely understood, and there is no reliable way to predict it. A widely-accepted mechanism is that the easterly phase of QBO can perturb the polar vortex through SSWs and sometimes lead to the early breakdown of the polar vortex in winter.[16,17]

More interestingly, a few climate studies involving multi-decade SSW events suggest the perturbation of solar activity on the polar vortex. It is found that solar forcing can perturb the late winter polar vortex (often in February but also can occur in earlier and later months), causing an early breakdown of the vortex in the form of SSW.[17-19] These studies are focused on the polar vortex dynamics or the corresponding impacts on the Arctic ozone hole. The possible link between the solar cycle and the extremely cold surface temperature through the SSWs and the polar vortex breakdown has not been reported.

Table 2: Summary of the ECE trend and its correlation with the solar cycle in all stations.

Station Location	ECEs trend	Impact of the Solar Cycle
Minneapolis, MN	Not clear	Not clear except the last SC
New York, NY	Increasing trend	Clear positive correlation with the SC
Houston, TX	Not clear	Positive correlation with the 1^{st} and the last SC, but not the 2^{nd} and the 3^{rd} SC.
Las Vegas, NV	Not clear	Not clear except the last SC
Death Valley, CA	Increasing in the most recent years	No correlation

Since the impacts of QBO and solar cycles are coupled together in a complex non-linear way; it is challenging to separate the SSWs due to these two factors quantitatively. Moreover, not all SSWs lead to a breakdown of the polar vortex. On the surface, not all extreme cold cases are due to the polar vortex. Therefore, a close correlation between the solar cycle and extreme cold cases is not expected. However, for those locations where most extreme cold cases are linked to the polar vortex, it is exciting to find a clue for the linkage between the solar cycle and the occurrences of extreme cold.

Assuming the polar vortex breakdown plays a major role in the ECE occurrences at some of the stations, we need to separate the impacts of the QBO and the solar cycles on the SSWs that lead to the polar vortex breakdown, at least qualitatively. In the right column of Figure 10, we applied a 4-year averaging on the number of extreme cold cases (the red line). Ideally, this averaging can help smooth out the impact due to QBO. The remaining trend would be due to the solar cycle and any other possible factors.

The solar UV irradiance (Lyman-alpha at 121.5 nm) is overplotted in Figure 10 (the black curve; right axis) to compare with the 4-year averaging results of ECE cases. The results are also summarized in Table 2.

For most stations, there is no solid correlation between the solar cycle and the 4-year averaged frequency of ECEs throughout the 50-year period. However, In New York, there is a correlation between the two. Even in the histogram without the 4-year averaging (left panel of New York results), there is a hint of the solar cycle effect on top of a gradually increasing trend of the ECE occurrences. To make the comparison more accessible, we applied a linear fit of the increasing trend of the ECE occurrences in New York, then removed this trend from the red line (4-year averaging) in Figure 10 and plotted the new result in Figure 11. The correlation between the solar cycle and the occurrence of ECEs is clearly shown, especially in the most recent three solar cycles. This correlation has not been reported in the literature. It must be noted that more detailed work needs to be done to confirm the correlation further and separate the QBO effects and the solar cycle effect quantitatively.

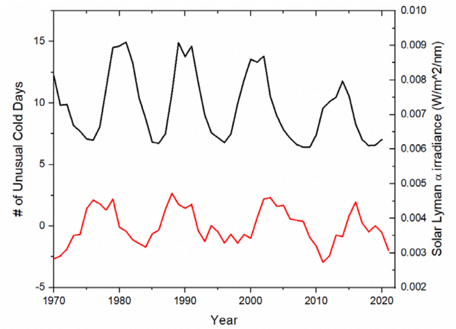

Figure 11: The 4-Year averaged and detrended number of ECEs (red line) and the solar irradiance (black line) in New York.

For other stations known to be affected by the polar vortex in the past, Minneapolis and Houston, there is a hint of the solar cycle effect in some of the solar cycles but not all four cycles during the investigated time period. The Las Vegas station is not expected to show any impact from the solar cycle, but there could be a weak correlation during the last solar cycle, although it is not very clear. The only station with no correlation is Death Valley, which is not surprising given that it is located at a very low altitude and blocked by the high mountains surrounding it.

During solar maxima, the higher solar activity and the higher solar irradiance lead to a weaker polar vortex and a higher chance of SSW, which results in a higher chance of the polar vortex breakdown. Once the polar vortex breaks, the Arctic cold air spreads southwards and eastwards. Depending on the strength, it could sometimes cover the entire east half of the U.S. and extend all the way to Texas. This impact is generally stronger on the east and north side of the U.S. and stronger in places with no high mountains to prevent the cold Arctic air from invading. Therefore, the stations in these areas are expected to be more affected by the polar vortex through SSWs than the south and western stations. And there is a higher chance to extract a solar cycle impact on the extreme cold cases through its parturition on the polar vortex. New York is a perfect example. Minneapolis and Texas also show some signals but are not very consistent. Death Valley is not expected to show any correlation, while Las Vegas is most likely not.

This could be the first evidence of the solar cycle's impact on the occurrences of extreme cold events at surface weather stations. More analysis with a larger number of stations or even satellite data needs to be done to confirm further what we have discovered. More quantitative studies using climate models could help separate the impacts of the solar cycle from other factors and confirm this correlation.

Conclusion

Using the daily temperature data from NOAA at five selected weather stations during the past five decades, we analyzed the trend of the extreme cold event frequency and its possible correlation with the solar cycle.

The absolute temperature cutoff is not a good way to define extreme cold events. The results using this arbitrary method would lead to an apparent decreasing trend of ECE cases in all locations. The more reliable method is to investigate the anomaly of the temperature. We first carefully extracted the long-term trend baseline and the average seasonal climate. The variation from the "normal" temperature determined by the baseline and the seasonal climate is considered an anomaly. The large negative anomaly outside the range of two times the standard deviation is considered to be extreme cold cases.

The results of this analysis method do not show decreasing trend at any stations. In New York, a clear increasing trend of ECEs is observed.

Using a 4-year averaging to smooth out the QBO effect, we can compare the resulting changes in ECE occurrences with the solar irradiance variation during the solar cycle. The station on the east coast, the New York station, shows a clear positive correlation with the solar cycle. In contrast, the stations in Minneapolis and Houston show some hint of the correlation during some solar cycles but not all. The low-altitude west station, Death Valley, shows no correlation with the solar cycle, while Las Vegas is not clear.

This could be the first evidence of the solar cycle's impact on the occurrences of extreme cold events at surface weather stations. More research needs to be done to confirm it further.

Future Studies:

This work covered five selected stations. Future studies should use a large number of stations covering various local climates and topographies on a global scale or even use satellite data at the lower troposphere to have a more comprehensive investigation to confirm our conclusions.

A more quantitative method could be used to accurately separate the effects of QBO and solar cycle on the polar vortex through the onset of SSWs. Climate models with and without built-in solar cycles can be used to investigate the detailed impact of the solar cycle on extreme cold cases and the mechanisms of these impacts.

Acknowledgments

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